Reversible Residential Air-Conditioners and Heat Pumps Using Carbon Dioxide (CO₂, R744) as Working Fluid

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INTRODUCTION

The current world market for reversible air conditioners (RAC) split-type units is roughly 30 to 35 million units per year. Virtually all of them use HCFC-22, R407C or R410A, which are powerful greenhouse gases with relatively high global warming potentials (GWP-values). Although the refrigerant leakages from HCFC and HFC RAC systems are relatively small, an alternative solution is to utilize refrigerants that do not have any negative impact on the global environment, such as the non-synthetic fluids ammonia, hydrocarbons and carbon dioxide. Carbon dioxide (CO₂, R744) is one of the few non-toxic and non-flammable working fluids that contributes neither to ozone depletion nor global warming. Due to its favourable thermophysical properties, R744 is regarded an interesting alternative to the HCFCs and HFCs in many applications including residential air-conditioners and heat pumps.

More than one million R744 residential heat pump water heaters (HPWH) have been installed in Japan, and 5 million units will be installed by 2010. R744 HPWH systems for residential and non-residential applications are now also available in Europe. Coca Cola has installed several thousand R744 bottle coolers, and in Europe several hundred R744 refrigeration systems both in transcritical- and cascade operation have been installed (www.R744.com).

There is an increasing interest for high-efficiency air-conditioning systems that can be reversed for heat pump operation. This article presents the main results from simulations and extensive testing of two R744 residential prototype air-conditioning systems for heating and cooling of residences.

SIMULATION AND TESTING OF R744 RAC UNITS

Prototype R744 Split-Type RAC Unit with 4-Way Valve

A prototype R744 RAC split-type unit and a high-efficiency state-of-the-art Japanese R410A RAC unit have been tested in a two-chamber calorimetric test rig (Jakobsen et al., 2006). The maximum compressor power consumption for the R744 and R410 units was about 2.0 kW and 1.7 kW, respectively. According to Eurovent the selected R410A reference unit had the highest cooling COP at the rating point of all the tested R410A reversible split-type units.

The prototype R744 RAC split-type unit was equipped with a Sanyo inverter-controlled two-stage rolling piston compressor, finned tube heat exchangers (HX), and a tube-in-tube internal heat exchanger. Round tube heat exchangers were selected due to the limited availability of Multi-Port-Extruded (MPE) heat exchangers, and the concern for water retention and frosting issues. The compressor was connected to an intercooler to enable cooling of the CO₂ gas between the compression stages. The CO₂ pressure in the gas cooler was optimized by means of a manual expansion valve and a low-pressure receiver (LPR). Figure 1 shows a schematic diagram of the prototype unit.

The heating and cooling demands in typical residential dwellings in Athens, Greece (hot, dry climate) and in Oslo, Norway (cold, dry climate) were estimated by using the ESP-r building simulation tool. The models were based on a reference two-floor dwelling located in an apartment building with four similar flats of 112 m². Simulations for a entire year were carried out for one hour time steps, using measured heating/cooling capacities and COPs for the R744 and R410A RAC units and climate data for a reference year. The Seasonal Performance Factor (SPF) in heating mode included the electric peak load (bivalent heating system), while the SPF for the R744 unit in cooling mode included intercooling between the compressor stages, which increased the SPF by roughly 5%. Table 1 shows the calculated SPF values for the RAC units in heating and cooling mode.
Table 1 Calculated seasonal performance factors (SPF) for the RAC split-type units based on measurements in heating/cooling mode in two different climates (Jakobsen et al., 2006).

<table>
<thead>
<tr>
<th>RAC System – Calculated SPF</th>
<th>Heating Mode</th>
<th>Cooling Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Athens</td>
<td>Oslo</td>
</tr>
<tr>
<td>R744 prototype – measured data</td>
<td>4.3</td>
<td>2.7</td>
</tr>
<tr>
<td>R410A-unit – manufacturer data</td>
<td>4.0</td>
<td>2.6</td>
</tr>
<tr>
<td>Relative difference in SPF, R744 vs. R410A</td>
<td>+7%</td>
<td>+4%</td>
</tr>
</tbody>
</table>

In **heating mode** the calculated SPF for the R744 unit was about 7% higher than that of the R410A unit in the Athens climate, and about 4% higher in the Oslo climate. In **cooling mode**, the R744 unit achieved the same SPF as the R410A unit in the Oslo climate, but about 17% lower SPF in the Athens climate. The results demonstrate that it is possible for a R744 RAC split-type unit to match the energy efficiency of the best R410A unit on the market in heating mode and in cooling mode in colder climates. However, further development and optimization of the R744 unit, e.g. by utilizing micro-channel heat exchangers, applying a compressor with a higher isentropic efficiency and/or using an ejector or expander for expansion work recovery, is required in order to achieve the same or higher energy efficiency in cooling mode in warmer climates.

**Prototype R744 RAC Unit with Air Flow Reversing**

R744 RAC units can be designed as split-type systems (Jakobsen et al., 2006). However, switching valves are challenging components and the most compact R744 heat exchanger concepts differ from state-of-the-art RAC HFC units (Hafner et al., 2008). A high degree of heat exchanger compactness can be achieved when utilizing Multi-Port-Extruded (MPE) tube heat exchangers. The costs of these efficient aluminium heat exchangers can be reduced when they are produced in large numbers, similar to concepts of mobile air conditioning units. Refrigerant distribution inside the evaporator header manifolds of MPE heat exchangers is another challenge due to the large number of tube ports. By replacing the expansion valve with an ejector the degree of mal-distribution will be reduced, since mainly liquid will enter the heat exchanger tubes. Good temperature fit between the CO2 and the air in the gas cooler can be achieved with compact MPE heat exchangers when the heat rejection takes place in the preferred flow configuration of cross-counter flow. Since heat is rejected over a large temperature range the heat exchanger design should minimize internal thermal conduction. Last but not least, uniform air side distribution is important in order to achieve a high system performance, i.e. the overall efficiency depends on optimized air flow arrangements.

There are two main ways of reversing the operating mode between cooling and heating. The refrigerant flow can be redirected by means of a 4-way valve or the air flow can be reversed. The former
system requires several additional valves and fittings, which adds extra costs and leads to increased pressure drop for the system and possible refrigerant leakage. A prototype low-capacity RAC unit has been developed in order to test the latter design, i.e. the application of air flow reversing for switching between the operating modes. The principle system layout for this concept is a turning table with a tangential placement of the heat exchangers as shown in Figure 2. Stationary fans are located in every corner of the RAC unit. Figure 3 shows a schematic diagram of the prototype unit.

![Prototype RAC unit with air flow reversing for switching between heating/cooling mode.](image1)

**Figure 2** – Prototype RAC unit with air flow reversing for switching between heating/cooling mode.

![Schematic diagram of the prototype R744 RAC unit including instrumentation.](image2)

**Figure 3**  Schematic diagram of the prototype R744 RAC unit including instrumentation.

The R744 RAC prototype system was equipped with an Embraco hermetic piston compressor with fixed rpm, inverter controlled fans, a four-row MPE evaporator, a four-row cross-counterflow MPE gas cooler, a thermal back-pressure valve (TBR), a back-pressure valve (MBR), an internal heat exchanger (IHX) and a low-pressure liquid receiver (LPR). The turning mechanism was a simple manual handle, but an electrical motor can also be used. When the evaporator needed defrosting a valve bypassing the gas cooler, the internal heat exchanger (IHX) and the expansion devices was opened for a short time. During defrosting the fans were operated at their lowest rpm or switched off. Since the air is drawn through the heat exchangers from ambient, special emphasis has to be given to enable removal of the condensed water drained out of the evaporator, since the absolute pressure inside the unit is lower than outside.

The R744 RAC prototype unit was tested at ambient temperatures between -12°C and +10°C (heating mode) and +32°C and +53°C (cooling mode). Figure 4 shows the main results (Hafner et al., 2008). The green dots represent the measured COP in heating and cooling mode, whereas the dotted lines in red and green shows the measured heating and cooling capacity for the unit. The solid-drawn lines in
red and green shows the COP in heating and cooling mode, respectively, when applying an improved compressor with 60% overall isentropic efficiency.

![Graph showing COP and capacity for R744 RAC prototype unit](image)

**Figure 4** Measured and calculated COP, heating capacity and cooling capacity for the R744 RAC prototype unit (Hafner et al., 2008).

**CONCLUSIONS**

A third-generation prototype R744 RAC split-type unit were constructed and extensively tested in heating and cooling modes. The test results were used for calculating the seasonal heating and cooling performance (SPF\textsubscript{tot}) for two different climates; Greece (Athens) and Norway (Oslo). The results were compared with manufacturer's data with verified rating points for the most energy-efficient Japanese R410A split-type unit available on the market. In both the heating and cooling mode in Oslo climate the calculated SPF for the R744 and R410A units were more or less identical. However, in the cooling mode in the Athens climate, the SPF of the R744 unit was about 15% lower than that of the R410A unit. Consequently, further development and optimization (applying ejectors etc.) of the R744 unit will be necessary before the R744 unit will be able to match or outperform the market-leading R410A RAC units in terms of energy efficiency. However, since the R744 unit already matches many of the better R410A units on the market, R744 must be regarded as a promising refrigerant in reversible air-conditioning and heat pump units for residential use.

An air reversing, turn-table air-conditioning unit was also designed and experimentally investigated. In contrary to conventional RAC units, the refrigerant circuit remains unchanged when shifting between air-conditioning and heat pump mode, since the air flow through the heat exchangers is changed. Since the function of the heat exchangers remains the same, they can be optimized for gas cooler and evaporator operation. The operational reliability will also be improved since the 4-way valve has been eliminated. The concept study has shown that a turn-table residential R744 air-conditioning unit is a viable option where both heating and cooling is required during the year.

**REFERENCES**

